Chapter 11

BIOPHOTONIC AND PHOTOBIOLOGICAL SENSORS: AN ATTEMPT AT A SYNTHESIZOR APPROACH

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Abstract

In order to try to apply nature-related-learned concepts to optical sensors and to smart structures, and after some considerations concerning the differences between biophotonic and photobiological sensors, some Sensory Physiology notions are presented. The influence of the subjective notions of perception are shown. Several examples are given of sensory illusions and the differences between seeing and interpreting. Different types of eyes, ranging from the compound to the mammalian eyes, are studied. A first interpretation of the previous facts concludes the paper as well as some considerations about the chaos as a possible tool to interpret them.

11.1 Introduction

All living organisms, in order to be defined this way, must have a set of organs that indicate the situation of their surrounding medium and how to adapt better to it. All these organs, making up more or less complex systems, are controlled in an overall way by the brain which, in the end, determines which option the aforementioned living organism can choose among the variety of possibilities.

However, for these organs to function, so the brain can dictate its orders, it is necessary that, firstly, certain elements (which we will call sensors) have carried out their tasks, which inform about what is happening in their surroundings. Whether it is cold or hot, night or day, whether the effort being made is bearable or not. This must be measured in the way which most easily helps the organism to adapt to its habitat.

Nature has continued to adapt, through a long process of trial and error, a complete set of different options which make up the distinct levels of the animal world. Each one of them has continued to orientate towards that function which is most important for the survival and continuity of the species considered. As the circumstances surrounding each species are generally very different, each one of them has been obliged, as time has gone on, to modify its sensorial organs separating itself, as much in configuration as in the processing of received information, from others which may originate in the same evolutionary tree.

The study of how the different organisms confront objectively analogous situations constitutes a school from which an infinity of lessons can be learnt. Nature has always been one of the best educators for teaching humans the most effective method to achieve a particular objective, when we have wanted to learn from it. It is obvious that, occasionally, the decisions taken by living organisms were not been those that man has later developed. The example of how humans fly today and how birds have done so since their beginnings shows that the lesson that could have been learnt from them was not the method that was finally adopted. But although the final solution was different, the concept is the same: man's vocation to fly, from times before Icarus, was taken from birds. It is difficult to imagine when and how humans would have taken off if in our surroundings there had not been other organisms doing so. Neither can it be imagined what would have sparked humans to wish to elevate to the skies if others had not been seen doing so around them.

The study of how different organisms accommodate to their environment, how they develop methods of seeing or hearing, of taking advantage of heat, consequently constitute an everlasting source of knowledge which cannot be ignored. And in the specific case that occupies our attention today, i.e. the analysis of the different sensorial organs of living organisms and more specifically of vision, can lead to the development of new artificial systems which bring about a more comfortable lifestyle or better use of resources. One part of this work will be dedicated to this type of study and will cover the group denominated *Photobiological Sensors*. A possible definition of these would be *"those sensors existing in living organisms for determining special and temporary characteristics of the environment by analysing the light received"*.

If lessons can be learnt from living organisms, to obtain them it is necessary to specify, as far as possible, what are the roots of their behaviour; how the different components making them up behave and what makes some structures behave in one way or another. The only way of achieving this knowledge is by measuring and analysing all the variations present in previous cases. These measurements, in every case, must be derived from the obtained data and a posterior processing of the information received. The first part of this process, the data collection, must be done using some type of sensor which converts the signal derived from the object phenomenon into a variable we can understand. Given the state of modern technology, this variable will nearly always have electrical characteristics, either voltages or currents, which suitably treated will lead to the desired results.

The initial data taking stage does not always have just one aim. According to the variable to be measured, there will be one type of element which adapts better to its characteristics than another. For example, to measure the torsion of a muscle a sensor which converts mechanical deformations into voltage signals will be required. The same element would be useless for measuring how the luminous intensity affects the retina or how Na ions pass through a neuronal membrane. For a long time, most of the sensors carrying out these functions were either based on phenomena which took advantage of, for example, the mechano-electrical properties of certain materials or were sensitive to variations of the phenomena to be measured, which they converted into variations of electrical currents. The number of phenomena which have been used in this transduction are numerous and, each day, new contributions appear which increase the number almost exponentially. One of the latest contributions, at least when referring to applications in commercial apparatus, is derived from the use of light as an agent capable of recognising, through changes in its properties, characteristics of the medium onto which it incides. This is the field covering what we have called *Biophotonic Sensors*. These sensors may be defined as *"those that are capable of detecting static and dynamic properties of living organisms through the use of light"*.

Finally, there is a third type of sensor which acts in a different area to the last ones. It forms part of the complete cycle of a particular biological process but not only supplying information, like the anterior ones. At the same time as capturing the relevant information, it uses this information to start a chain reaction of essential biological processes, not only for relating the living organism to its surroundings but for its own development. The best known case would be the capturing of light by vegetables and their use of this light to generate organic material from inorganic material. This new group of sensors could be called *Photobiogenerator Sensors* but it will not be covered here. A first definition of these sensors could be *"those responsible for taking advantage of light to generate organic products"*.

11.2 What must be sensed and how. Sensory Physiology Notions

11.2.1 General Considerations [1]-[7]

As has been mentioned before, living organisms' awareness of their surroundings and the events taking place there does not usually come from direct contact, but through a specialised set of sensory organs (eyes, ears, skin as a tactile organ, the tongue for tasting, the nose for smelling...). Each organ is made up in such a way that it only responds to a particular type of exterior stimuli, transferring this information to the *Central Nervous System*, CNS.

The set of stimuli to which a particular sensory organ responds can be partially explained in phylogenetical terms. Only those environmental factors that are essential for the survival of the living organism are captured by its sensory elements. So, for example, of all the electromagnetic spectrum, the human is only capable of perceiving radiation between 350 and 800nm, approximately, which is the part of the spectrum at which the atmosphere is relatively transparent. X-rays, or gamma rays, or radio signals, have no effect . On the contrary, a certain part of the infra-red zone does affect another set of human sensors, the skin, giving it the sensation of heat but the eye is insensitive to it. In other species, this adaptation is very different. A certain type of fish which lives in turbid water is capable of detecting very small changes in the electromagnetic field surrounding it and so, it can sense the alterations produced by the electric discharges produced by its fellows.

Each sensory organ, in response to its corresponding external stimuli, gives a series of signals, sometimes called *"sensory impressions"* that can vary in intensity but which are alike in form and characteristics. A set of equivalent sensory responses produced by a particular organ is called in sensory physiology, *"modality"*. These modalities include the classic five senses plus a whole set of different sensations, originating from alterations in the external medium like, for instance, heat and fear. Further more, there are others derived from the organism itself and from its particular internal situation. The feeling of hunger, or of lack of oxygen, must correspond with the information given to the brain, that the conditions for the organism are not the most suitable for survival. The number of possible modalities is thus very much greater than the conventional five senses. It should be noted that on many occasions these modalities are inter related. Due to this, the general state of a living organism is the result of the co-ordination of all these modalities. In many situations, it is necessary to analyse the information coming from many sensory organs to reach a complete understanding. This point must be highlighted since it is of fundamental importance in the design of any artificial detection system of external parameters.

Within any of the probable modalities, a set of different variations of the resultant signal corresponding to the different possible inputs can be extracted. This is what is known as *quality*. In our specific case, vision, the differentiating qualities of an optical signal might be its content of red, blue and green or its brilliance.

A sensory signal of a particular quality is determined by the living organism when adequate external factors incide on the corresponding sensory organ. The factors determining the sensory impression of a particular quality are known as *specific sensory stimuli* or simply, *stimuli*. The stimuli acquire a quality owing to the reaction provoked in their corresponding detector cells in the corresponding sensory organ, that is, in the *receptors*. These cells are configured in such a way that they provide the greatest possible response to a stimulus of specific characteristics. In the case of the retina, each receptor contains a pigment which absorbs light of specific quality. In general, the specific stimuli give rise to changes of potential in the receptor cells, called *receptor potentials*, which in turn generate *action potentials* that are conducted through the nervous fibres to superior levels. These action potentials are analogous for all the sensory qualities. Once again, we emphasise this fact for posterior reasoning. The information quality is determined solely by the path followed to the information processing centre, in most cases, the brain. For several reasons, the case can arise that the sensory element is stimulated by an extraneous cause. In this case, the living organism will believe it feels something similar to what it would have felt if the stimulus had been real. An example would be when we hit an eye, which causes a *"seeing stars"* sensation.

Independently of the sensory impression received by the living organism, due to its modality and its quality, the additional element which the impression possesses is its intensity. Thus, the *quantity* of a sensory impression corresponds to the strength of the stimulus that incides on it. The point of origin of the intensity curves of a certain response is very significant, since it determines the value of the minimum stimulus that can produce an appreciable sensation in the living organism. This point is known as the *threshold stimulus*.

The sensory impressions are not only characterised by the modality, quality and quantity but also occur at *a particular instant and in a particular place* in the surroundings of the living organism. Our eyes do not simply see light but capture images of the environment space. These images succeed one another in time, and they can also be recalled as having been associated with a particular point in time.

The aforementioned concept of *sensory impression*, deserves a more precise explanation than that given up to now. It is used to design the most elementary units, that is, the basic elements of sensory experience. For example, the colour "blue" would be a sensory impression. However it is very strange that isolated sensory impressions are received. Normally, a set of them arrives. This set is called *"sensation"*. As a general rule, we could say that a pure sensation is accompanied by a posterior interpretation, that is related to what has been previously learnt or undergone. The result of all this is called *perception*. For example, a perception exists, when one says *"this is a table"*.

11.2.2. Correlation between phenomena and perception. Objective and Subjective sensory physiology.

The chain of correspondence between the exterior phenomena and their perceptions is synthesised in Fig. 11.1. The rectangles indicate basic phenomena at different levels. They are joined by arrows which indicate projection, not causality. These arrows establish the relationship correspondence mentioned previously. So, the excitation of a nerve can be considered as the mapping of a sensory stimulus and the perception as a mapping of the sensory impressions. The concept of "mapping" denotes the existence of a unique, defined representation, so that points of one object are associated to points of another object. In mathematical terms, it could be defined as a unique association between members of two sets ($x \in A \Rightarrow y \in B$). The object itself does not cause its representation. The projection takes place thanks to the presence of a suitable device. So, the projection is not characterised by only one object but by the special projection conditions.

Thus, the blocks of Fig. 11.1, denoting the different levels indicate the conditions which must be fulfilled for the projection to be done in each case . The conditions of the medium, appearing on the left of the Figure, are only sensory stimuli if they interact with the adequate sensory organ. In the same Figure, in an analogous way an excitation, sent from a sensory organ to the CNS and processed there, becomes a sensory impression or a sensation only if the CNS is associated with a subject capable of having a certain degree of consciousness. The projection relation indicated by the arrows from the events of surroundings to the integrating processes in the sensorial part of the CNS can, in principle, be described as physical and chemical processes in the structure of the living organism. This type of physiology is thus *called Objective Sensorial Physiology*. On the contrary, the projection between these objective phenomena (a sensory stimulus and the consequential processes in the nervous system) and a conscious sensation can not be described in function of physical or chemical processes. The field of sensations and perceptions, and how they relate to the sensory stimuli, is thus called *Subjective Sensorial Physiology*.

Sensorial Physiology may be divided into two parts. The first consists of the descriptions of the nervous system responses to an exterior stimulus. The second consists of the analysis that the subject receptor makes of its own perception and sensations. If, from the former, information can be extracted about the nature of the mechanism of capture and supply of information to the brain, from the latter, if studied and understood, it would be possible to determine how the living organism confronts its surroundings and why it behaves the way it does. In the extreme case, it would facilitate the understanding of the process of consciousness.

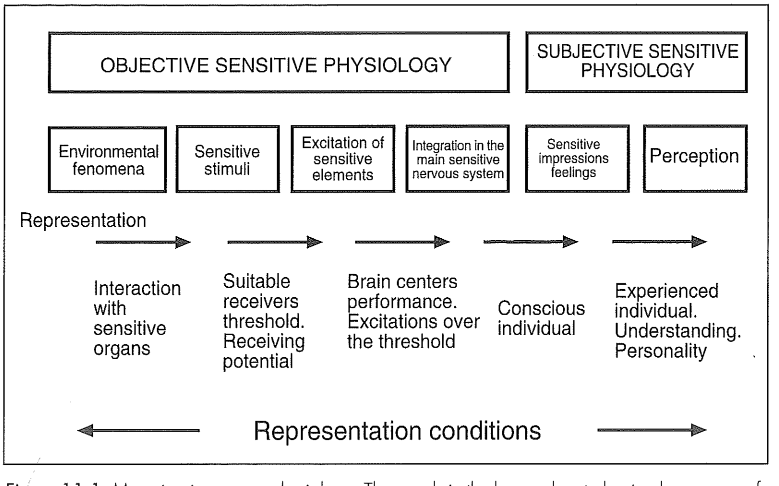

Figure 11.1. Mapping in sensory physiology. The words in the boxes denote basic phenomena of sensory physiology and the arrows between them indicate the "mapping". Below the basic phenomena, the conditions for mapping are shown.

11.2.3. Working tools: Sensory illusions. To see and interpret.

The study of how signals are captured in the different sensorial organs, and how the living organism extracts information from them in order to achieve a desired goal, constitutes one of the most prolific fields of neurobiology, sensorial neurophysiology and in general, of any of the branches of neuroscience. The experimental methods have developed since the end of the last century and, with one name or another, have provided data that little by little, has formed a structured area of knowledge. In general, we know which processes take place in photobiological sensors and how the signals generated in them get to the superior processing centres, that is, the brain in the case of the vertebrates. We know which area of the cortex processes each type of signal and, in the case of visual signals, which zones of the cortex detect particular characteristics of the objects registered by the retina.

Even though a great part of the neuronal architectures making up the first information processing layers have been known for some years, it is still necessary to find out a lot about what processes take place in the superior layers of the brain, which lead to the living organism having complete consciousness of its existence. One of the factors which causes difficulties in getting an in-depth knowledge the function of the brain, specifically the human brain, is the difficulty of carrying out experiments on the brain. Most of the data available in human neuropyschology come from the study of pathologies. When particular faults in behaviour, or with reception of an external stimulus, have been found to be linked to abnormal states of a certain part of the brain, through accidental injury or degeneration processes, that part of the brain is determined to act as the basic centre of the process. So, for example, injuries in the left of the brain are known to give rise to aphasia[1] phenomena,

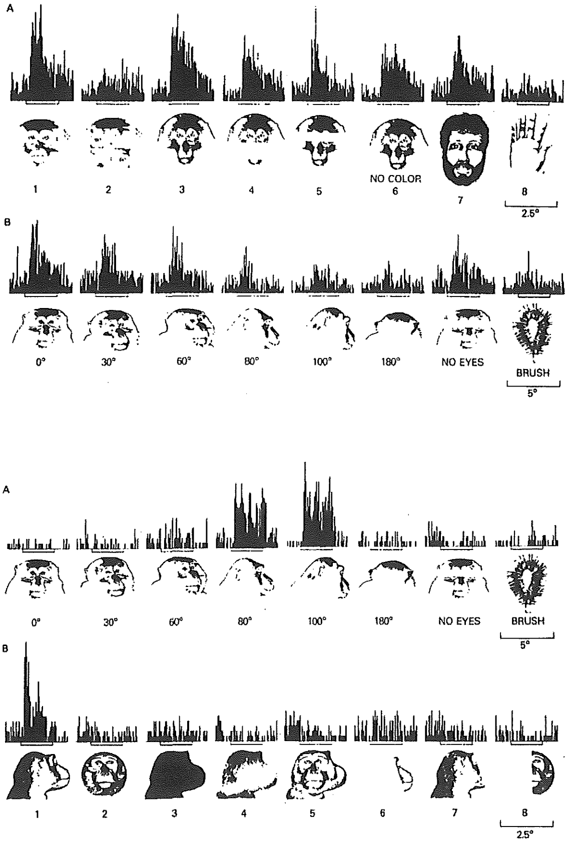

Figure 11.2. Responses of a neuron within the superior sulcus interferotemporal (IT) cortex that responds selectively to faces.

[1] *Aphasia* is a language problem which impedes the patient from speaking clearly and which is derived from injuries to a specific part of the brain, situated on the left.

while if they occur in the occipital lobules, they lead to anomalies of vision. In the same way, commisurotomy[2] operations, carried out on patients who suffer epileptic fits, showed the loss of a series of coordination actions between the preferential tasks carried out by the two cerebral hemispheres. The experiments carried out on animals allow us, as is logical, to determine a set of perturbations that are common in a wide range of living organisms including man. Using this starting point, the function of any part of the brain can be deduced. But the characteristic human tasks like speech or reasoning can not be explored through experimentation on animals. Other much more complex phenomena are also sometimes impossible to extract from this type of experimentation. For example, the stimulus of a particular part of the brain which gives rise to a sensation of green circles, can only be determined on a human who can tell the experimenter what he is feeling; an animal *"will see"* the green circles but can not communicate to the exterior. Of course, there is a series of techniques which determine what part of the brain, in animals or humans, is being stimulated by certain exterior stimuli. For example, Fig. 11.2 shows the case of the responses of a neuron of the superior temporal sulcus in the inferotemporal cortex of a monkey. As is obvious, this neuron has the property of responding selectively to particular faces which have very well-defined features.

In the case presented in Fig. 11.2.a, the response to two monkey faces and one human one is clear; if the features were altered with respect to their habitual positions, the re-

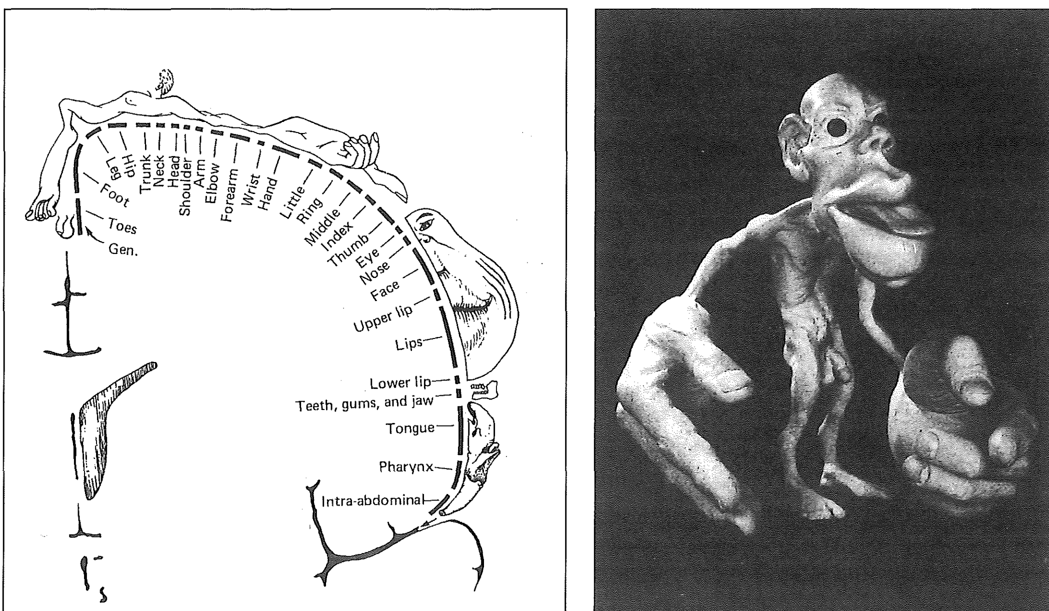

Figure 11.3. (a) Illustration of the primary somatosensory regions corresponding to different parts of the body. (b) The misshapen appearance of this little man, or homunculus, reflects the disproportionate areas of the somatic sensory cortex devoted to different parts of the body.

2 *Commisurotomy* consists of the particular or total section of the *corpus callosum* in such a way that the two cerebral hemispheres lose part of their habitual connection.

sponses were minimal. In Fig. 11.2b, we can see another neuron of the same zone which responds preferentially to the profiles of the same faces.

In this way, the parts of the brain which specialise in specific sensorial processes have been characterised. Fig. 11.3 [2] shows a simplification of this, indicating in which region of the cortex a particular type of stimulus predominated over others. It also shows the representation of a homunculus with dimensions proportional to the part of the brain destined to each part of its body. As can be seen, the hands (specifically the thumbs) would be among the most voluminous zones while other parts of the body, which we believe to possess great sensitivity, require a very small area of the brain and, consequently, in the homunculus they have a quite small size. It should be noted that each animal has a different type of homunculus.

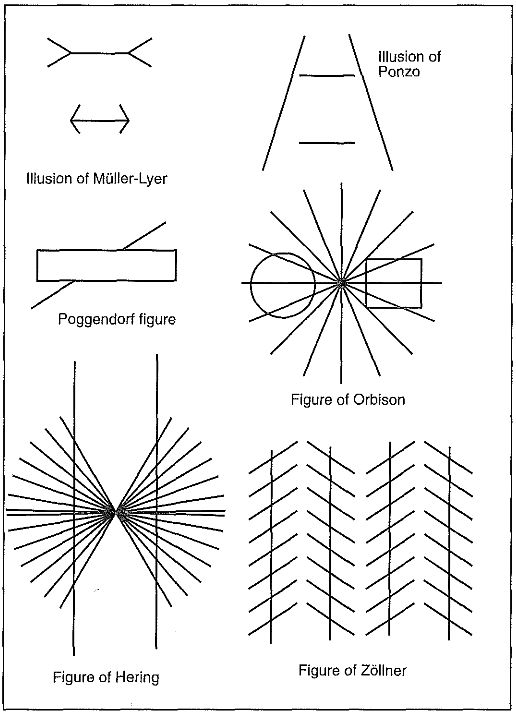

Figure 11.4. Examples of illusions in form perception.

Confronted with the problem of experimenting on live humans, we are faced with a doubt about how to carry out measurements and observations on them which determine the behaviour and sensations produced under particular stimuli. It has already been said that the observations of some clear pathologies allows the characterisation of which regions of the brain govern certain actions. Another study method is derived from the whole set of non-intrusive experiences which was initiated at the beginning of the century and made up what is called "Gestalt"[3]. This school, more psychological than neurobiological in character, attempted to identify a series of principles and limitations which govern the interpretation of the images. These interpretations were guided by a global behaviour which originated in the interactions between the characteristics of the object or image under inspection. Some of the most characteristic phenomena are shown in Fig. 11.4 and they are mostly well known, so it is unnecessary to go into more detail.

If at the beginning of the century, when this school was in vogue, the interpretations were, as has already been said, more of a psychological than neurophysiological nature, nowadays many of these phenomena or visual illusions as they have been called, can be explained in the light of the knowledge that exists of neuronal architecture or the visual system.

Thus, for example, Fig. 11.5.a shows one of the most characteristic cases of this fact. As can be seen, it is made up of black squares distributed in a regular way. The sensations that it gives the observer is that the intersections

[3] The German word "Gestalt" means shape, figure, but its concept in this case would be of "an organised whole in which each individual part affects the rest, the whole being more than the sum of its individual parts".

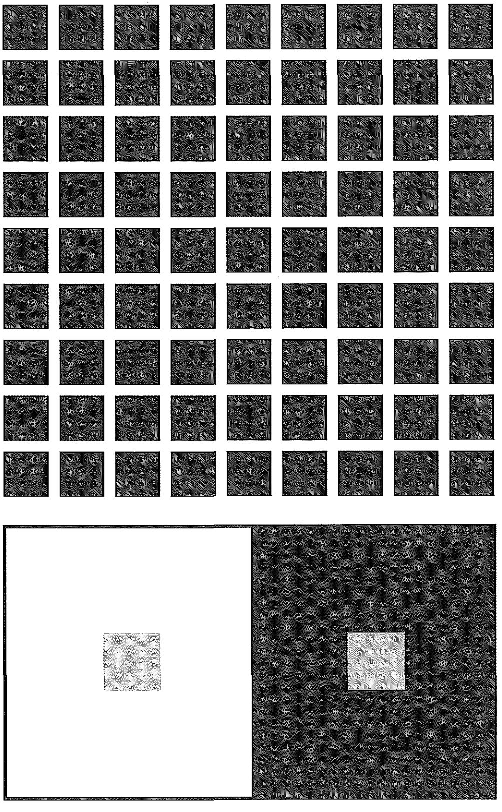

Figure 11.5. (a) The Hermann grid: illusory dark spots are seen at the intersections of the white bars. (b) Simultaneous contrast: the two grey squares are of equal luminance but appear different in brightness because of the background they are seen against.

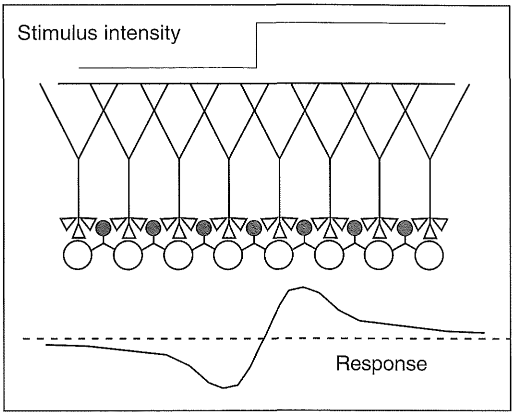

Figure 11.6. Lateral inhibition will exaggerate the response of second-order neurons to an edge, compared to the uniform areas on each side.

of the white lines which separate them, in spite of being just as white as the rest of the lines, seem to have a slight greyish tone. Something similar, although with a different root, is shown in Fig. 11.5.b. In this case the sensation is another. The same grey square appears over a black background and a white one. Although, as has been mentioned, in both cases the grey square is identical, in the case of the black background its appearance is lighter than in the case of the white background. The justification of these phenomena can be seen, in a simplified way, in Fig. 11.6.

If the second order neurons (like those sketched with the form of a white circle in Fig. 11.6) are excited by the signals coming directly from their corresponding receptors, but undergo an inhibition process due to the interneurons (those appearing as black circles in the same Figure), the result, as can be appreciated, is an increase in their response, when they are in the unilluminated zone, and a decrease in the dark zone. This contrast enhancement effect is called lateral inhibition when it refers to the neurons supporting it and, among other phenomena, it gives rise to the different behaviours of the gaglion cells of the retina.

An equivalent phenomenon is that of Fig. 11.5.b. Here the phenomenon, also of contrast, has a different effect although its root is the same. The contrast, referring to the visual perception in this case, is simply the relationship between luminosity of those adjacent parts of the image shown here. A general property of the sensorial perceptions is that the sensation due to the contrast between two zones is reinforced with respect to the objective parameters. Thus, when a dark zone is seen over a bright one, the border of the dark one appears darker then the middle zone which over the light zone appears as a slightly dark band.

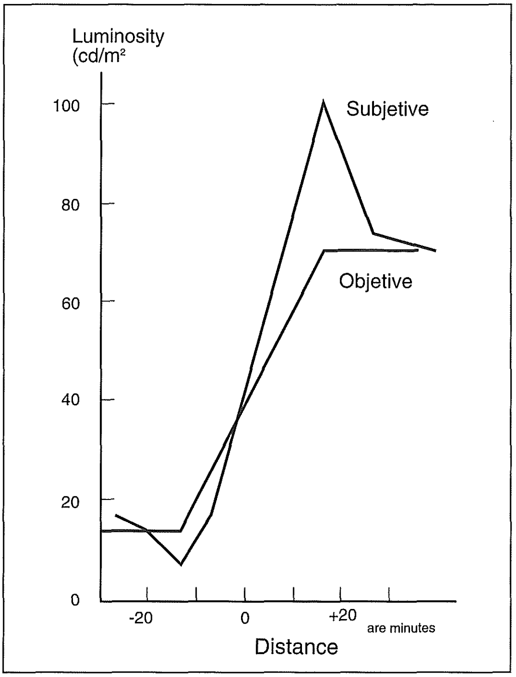

Figure 11.7. Contrast enhancement. Transition from a dark area on the left to a light area on the right. The lines represent values along a line perpendicular to the edge (position 0 on the abscissa). On the ordinate is the brightness of the viewed surface. The "Objective" curve shows the brightness distribution measured with a photometer and the "Subjective" curve the distribution perceived by a normal person.

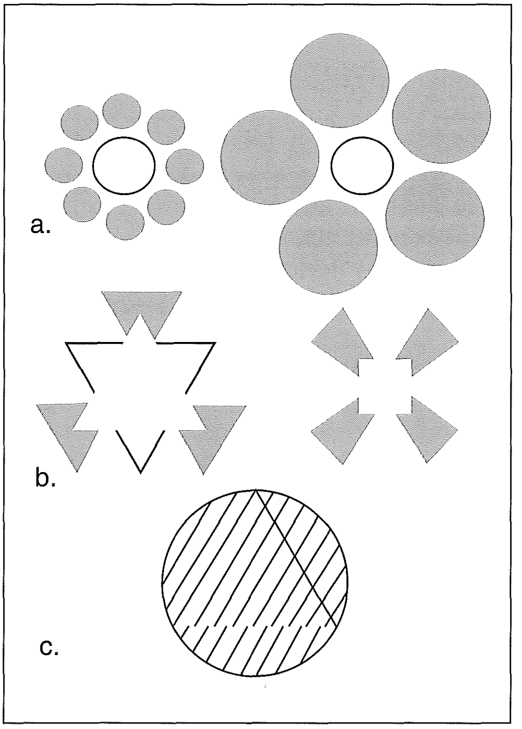

Figure 11.8. (a) Illusions in perception of shape: the central circles are the same size in each of the two figures. (b) Examples of illusory contours. (c) Where is the triangle in the right panel? Its right flank is perceived as drawn, and its base is perceived although not drawn, whereas its left flank is drawn but not perceived.

In Fig. 11.7. [1] the result of an empirical test is shown in which an observer can see a dark region to the left and a bright region to the right. The object luminosity, measured with an electronic sensor, is represented in the graph lines. The continuous one is what the observer can appreciate and it corresponds to the distribution of subjective luminosity. As can be seen, the line of passage from one zone to another is more pronounced but, at the same time, it has a maximum in the light zone and minimum in the dark one. The two appear at some 10 minutes of arc. Another fact which appears in the curve is that between 0'and -20'the luminosity seen is less than what really exists. This is clear proof of the *"inhibition"* effect. The same occurs, but in the opposite sense, between 0 and +15minutes. These effects, which are synthesised in a paradoxical sentence: *black is white when the background is brilliant*, receives the name of "edge reinforcement" and the regions with different perceptions to those really existing are known as "Mach bands".

If the living organism can appreciate different tones and illuminations to those seen by an objective sensor, at the same time it is capable of seeing figures which do not exist or, on the contrary, not seeing parts of figures which exist. In the same way it can be believed that figures if the same size are different, due to its relationship with the rest of the objects surrounding it. Some examples of this are shown in Fig. 11.8.

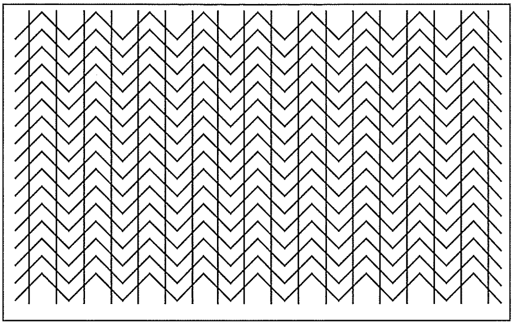

Figure 11.9. Variation of the Zöllner figure: the lines are in fact parallel.

In Fig. 11.8.a. the case of two circles of the same size can be seen where, due to the size of the surrounding circles, they appear to be notably different. Fig. 11.8. b. corresponds to the apparent existence of a triangle and a square, which in reality do not exist, and in which the brain itself adds the missing parts. Finally, Fig. 11.8.c. shows the paradoxical case of a triangle made up of a side which exists and can be seen, a side that does not exist but can be seen and another that exists but which can not be seen.

Lastly, and as a patent example of the influence of the background on the appearance which we perceive of objects, in Fig. 11. 9. the case of a set of parallel lines is shown, where due to the angular background, they appear to be lines forming a non-0 angle (amongst themselves).

At the same time as the impression of an object is felt in the brain, due to the surroundings, it is necessary to take into account another essential factor; this does not derive from what is present in an instant, but from what is stored in the memory, that is, the reflection of past situations. Some examples can help explain this. One of the clearest appears in Fig. 11.10. The Figure shows something which, on first impression, looks like the two halves of an egg box. The upper figure would be the concave part on which the eggs are located, the lower the top, that is the convex part, which covers the eggs.

If the two figures are turned 180°, it can be seen that the interpretation remains the same: the upper part is still the support and lower part, the top. The reason for this phenomenon is based on the notion that we have that light "always" comes from above. If we could forget about this, it would be impossible to say which is the concave and which the convex.

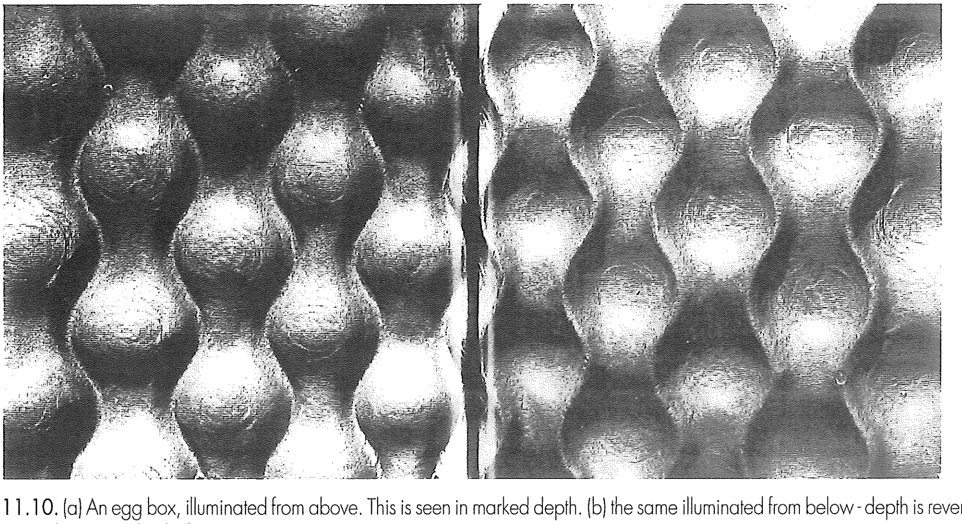

Figure 11.10. (a) An egg box, illuminated from above. This is seen in marked depth. (b) the same illuminated from below - depth is reversed. (Try reversing the page: depth changes)

Situations like those that have been presented in the anterior paragraph are quite common. In fact, behind many of them there is a strong component of previous experience. In other cases, it is the environment where we have lived, and finally, in others, the cultural and social aspects of where we live. So, for example, a great part of the optical illusions shown in Figs. 11.4 and 11.9 would not be appreciated by Zulus with no previous contact with the western civilisation. This is because their culture is a circular culture, in which the straight line is almost non-existent. Their houses are circular and the roofs are conical; the fences limiting their properties are almost never straight. Western civilisation is, on the contrary, based on the straight line and all our sensations, our notions of perspective, are based on what we have seen around us since birth.

It is curious to remember that the concept of perspective did not appear in western art until the Renaissance. Neither the Egyptians nor the Greeks had it. The eastern cultures also took many centuries to introduce it. Nowadays, if an inhabitant of the jungle, a bushman, is taken to an open space in which there is a house a long way away, he would be unable to determine its size and, in many cases, would say it was a small house in which he could not live. There is a famous anecdote about some doctors who go to Africa to combat a plague of tse-tse flies. They go to a tribal village, and with the aim of finding out where they could find the plague, they showed the tribe a page with a drawing of one of these flies. The native who saw it, without batting an eyelid, indicated that he was not surprised that they had problems with that fly because it was much bigger than any of those around.

11.3 Capturing light in a Visual System

Of the different parts making up the visual system of living organisms, possibly the most significant in terms of its external image, is the light reception system, that is, the eyes. Although the signal received by them is later processed in different ways by different living organisms, here we will concentrate on this part of the visual system, specifically, on the elements that capture the light, without going further into the posterior processing. We will only consider the part of the photobiological sensor which receives the luminous radiation.

11.3.1 Different types of receptive elements. [3]

One of the most interesting problems when studying the differing evolution of species is to justify the enormous variety of light sensory organs in living organisms. Although each species has adapted its sensory organs to its corresponding environment, in the same environment there may be similar species which have evolved in completely different ways. On the other hand, given the importance for any organism of knowing where it is, all the different levels of the animal kingdom have special ways of coping with this necessity. From unicellular organisms to the most complex ones, all have visual systems which can respond to the relational problems they may face.

Thus, while in unicellular organisms there are very simple structures giving access to the information carried by light, which cannot really be considered as a true visual system, in superior structures there are sets of cells available with more or less sophisticated architecture. These cells can be dispersed throughout the surface of the body, as is the case of earthworms, or structured in groups, mostly in small depressions in the skin, in which there is an initial image formation.

Some of the interpretations of these initial structures being located in minute superficial depressions, are based on the theory that in this way they are protected from possible external glare, therefore reducing the possibilities of capturing moving shadows. According to some historians the Greek astronomers located their star observation instruments inside deep wells. This allowed them to watch the stars comfortably during daylight.

The most primitive eyes are found directly located on the animal skin in a tiny cavity. This configuration had the danger that external particles are deposited on it with the resultant loss of vision. As a consequence, superior species developed protective membranes over these cells which impede the deposit of particles. When, through more or less intentional mutations, this membrane became thicker at the centre, it constituted the first lens, which almost certainly, at first, had the simple purpose of increasing the light intensity in the central zone. Later, this line was used for the formation of images.

A remnant of this type of structure can be found, for example, in limpets and is called *"ocellus"* (Fig. 11.11.a). Many coelenterates show more or less developed variations and they are therefore, along with neuromasts, one of the first sensorial organs studied in phylogeny. Its functions are essentially as light intensity sensors. In fact, it seems that it functions in a quite effective way since many invertabrates continue using it as an essential element in the active development in the corresponding medium. Many social insects maintain it.

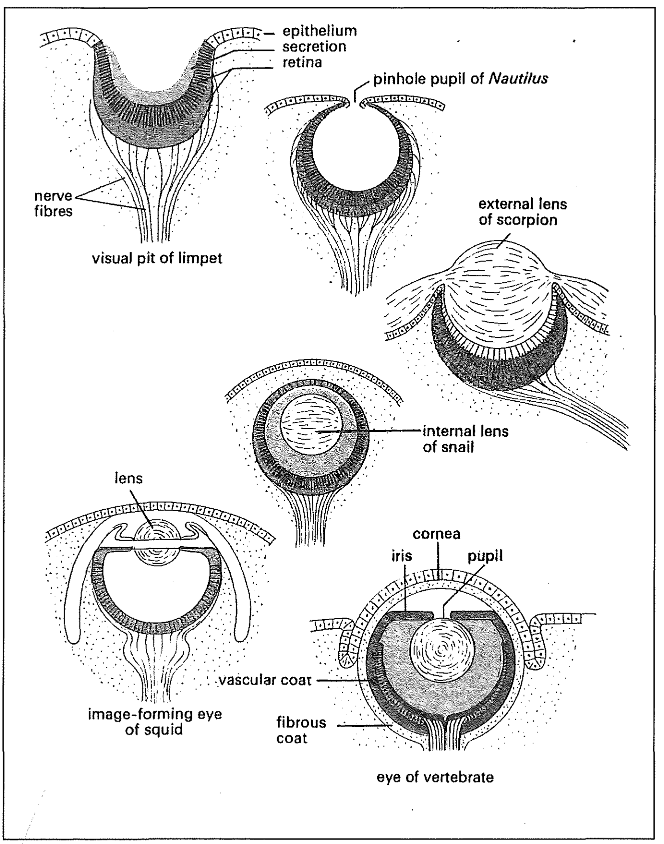

Figure 11.11. Different types of eyes. Details are given in the text.

However, so that the eye gives real vision it is necessary that it has a means of forming an image. For this, there are various forms, in many cases, that have also been used by man in some of the instruments that have been developed. The most simple is made up of a small orifice which opens into a cavity containing the photo-receptors at the bottom. It is the same principle as the dark chamber, widely used in the last century to form images in closed rooms (remember the spectacular example in Edinburgh) or for the first photographic camera. The light rays pass through the orifice and project an image of the exterior onto the back where the light receptors are located. This is the case of the organism denominated *"Nautilus"* (Fig. 11.11.b) which, because of its characteristics, only functions adequately when it is in a very bright environment. In this case, the inside of the cavity is full of sea water which is the medium in which it moves. It is curious that the inside of any eye of a higher animal is also full of an equivalent liquid with a high concentration of Na.

Other forms derived from the anterior forms are show in Figs. 11.11 c-e. The eye of a scorpion can be seen (Fig. 11.11c) in which the lens has been formed by a thickening process in the protective outer layer of the sensorial cells. In contrast, the eye of the squid can be seen (Fig. 11.11. e), in which a truly spherical lens projects a more or less distorted image of the exterior world onto the layer of photoreceptors. Between them, the eye of the snail (Fig. 11.11d) can be seen, with another spherical lens, but in this case located in the centre of a sphere practically covered in photoreceptors.

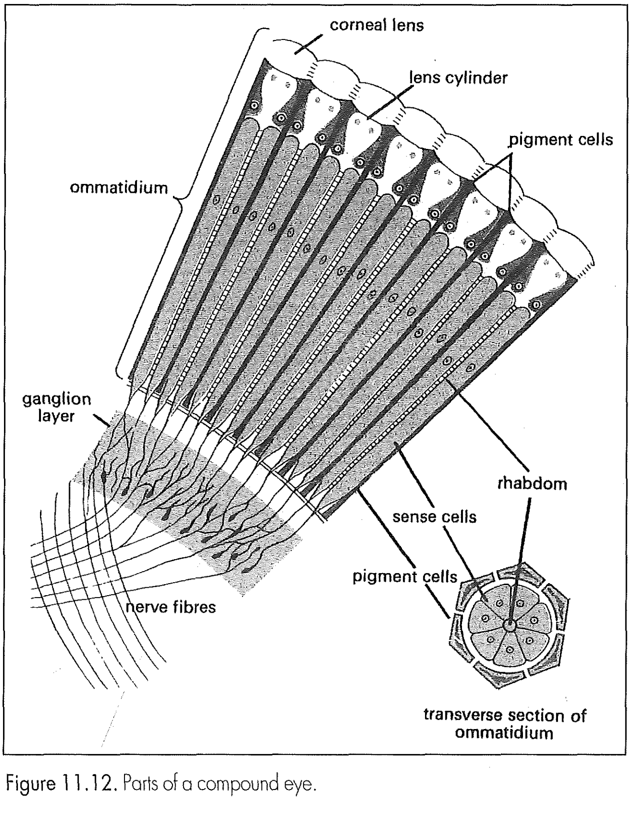

Figure 11.12. Parts of a compound eye.

11.3.2 Compound eye.[3],[8]

One of the most efficient ways of making up an image is found in the eye of some insects. This is the well-known *"compound eye"*, which as can be appreciated, is made up as a very large set of small channels through which the light is conducted towards the sensorial element (Fig. 11.11f). This is characteristic of the arthropods and its most usual configuration is detailed in Figure 11.12. As can be seen, behind the face of each one of lenses there is a new lens, in this case cylindrical, through which the light is guided to incide on sensorial elements. These are made up of seven cells grouped in a nucleus with a similar structure to a daisy. The whole set is given the name *onmatidium* and its cross section shown in Fig. 11.12b, has a regular hexagon shape.

One of the problems considered is the characteristics of the world as seen by an animal with a compound eye. In principle it may be thought that it would see a collection of worlds, each one coming from one of its eyes. However it seems certain that there is not a retina for each ommatidium, but that from each group of receptors a simple nerve fibre derives. Each ommatidium receives the image corresponding to the visual field in front of it and the set of all these signals is the final image seen by the animal.

These eyes have a very peculiar mechanism to adapt to light and dark. Each ommatidium is separated from the surrounding ones by a conical structure with a black pigment. In cases of intense light, they are isolated from each other due to this pigment. But when the external illumination is low, or under orders from the brain, the pigment is displaced towards the back, where the receptors are located, in such a way that the light can pass from one ommatidium to another, with the consequent improved performance. This increases the sensitivity of the eye although the indirect result is the decrease of the visual sharpness.

Another fact which seems important is the working method of the cylindrical lens which carries the light from the entrance lens to the photoreceptors. The conduction is carried out thanks to its guidance capacity which derives from its greater refractive index in the centre then at the surface. That is, the conduction is completely analogous to how it is carried out in a gradual index optical fibre.

As a conclusion of all the above, and according to A Knowles and J A Dartnell, the advantages of this type of eyes are, among others, the following;

"*(1) Its great depth of field makes it very sensitive to movement in relatively long distances*

(2) The comparatively short path that the light must take to enter in the ommatidium makes the losses in UV minimal. This, along with the little distortion produced, in contrast to the chromatic aberrations of the lens systems, make it possible to work within a wide range of wavelengths.

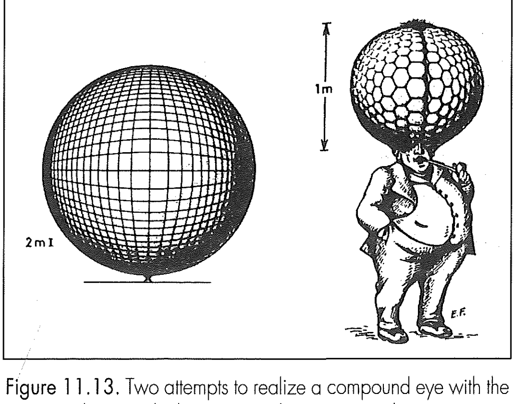

Figure 11.13. Two attempts to realize a compound eye with the same resolution as the human. Details are given in the text.

(3) The receptor cells are made up in such a way that the eye can be sensitive to the polarisation of the incident light."

However, as is logical, along with these advantages there is also a series of disadvantages which merit attention. The most important refers to the capacity to differentiate points more or less close in the visual field which the compound eye includes. This resolution depends on the size of the lens with which one looks. The bigger it is, the smaller the diffraction image generated. This image, when it is due to a point source, is the Airy disc, whose radius, r, from its centre to the first dark ring is given by

$$r = 1.22\,\lambda/D \text{ radians} \tag{11.1}$$

or for a width, w, at half of the maximum intensity, by

$$w = \lambda/D \text{ radians.} \tag{11.2}$$

Where λ is the wavelength and D the diameter of the aperture. The Rayleigh criteria assumes that two particular sources can be distinguished as separate if the maximum of one coincides with the first minimum of the adjacent one. That is, if its angular separation is greater than $1.22\,\lambda/D$. If this is applied to a bee, whose lenses have a diameter of 25 μm, it gives a resolution limit of 0.024 radians, or 1.4°, when the wavelength is 0.5 μm. On the contrary, the human eye, with a pupil of 2.5mm, has a limit 100 times less, that is, 0.84 minutes of arc.

Nevertheless, the adequate reception of an image must also be based, as well as on lens characteristics, on a suitable and correlated number of receptor elements. In the eye of mammals this problem, as will be seen further on, does not exist: the bigger the eye the better the diffraction image and the greater the number of available receptors. On the contrary, in compound eyes, the bigger the lenses, the smaller the number of receptor elements that can be activated. Without going into more details of this topic, which can be seen in the specialised literature, it is curious to consider what the compound eye of man would be like, if we wished it to have the same resolution as the actual eye has. Mallock, in 1894, was the first to determine that a compound eye, with an analogous resolution to the human eye, that is, of around 1 minute of arc, should have a diameter of around 19 feet, that is, some 6 metres (Fig. 11.13a)

In 1976, Kirschfeld made an analogous estimation but reducing the above mentioned resolution to the fovea alone, making it decrease drastically as we go away from it. The result is that it should have a diameter of approximately 1 metre (Fig. 11.13b).

The last point to highlight with respect to compound eyes is that the earliest known example of them is in some fossil remains of trilobites, which lived some 500 000 000 years ago. In some species of trilobites, the compound eyes were very developed, being made up of several thousand eyes. In the current examples, the number is more than thousands, reaching millions at times.

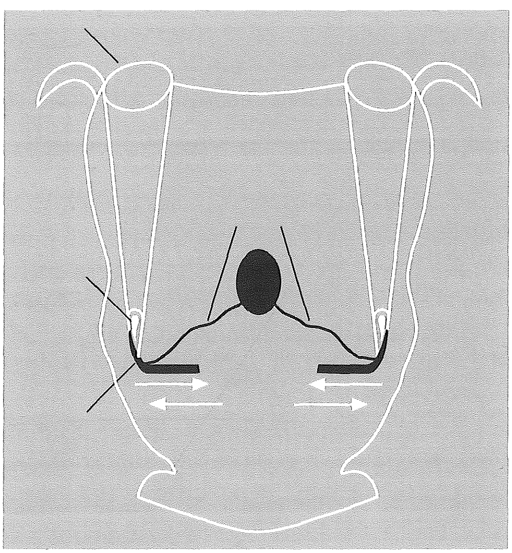

Figure 11.14: A living female specimen of a microscopic copepod. Each eye has two lenses: a large anterior lens and a second smaller lens deep in the body, with an attached photoreceptor and single optic nerve fibre to the central brain.

11.3.3. A Last Case [5]

As a last curiosity in the little gallery of eye types presented here, there is room for the case of one of the "test" examples which nature has done over the years. It refers to the *Copilia*, an animal of the family of Copepods which is smaller than a pin head. The female has a pair of image-forming eyes which are neither like the vertebrates'eyes, nor the compound eyes we have just seen, but which in a certain way behave like a small television camera (Fig. 11.14).

Each eye contains two lenses and a photoreceptor, similar to the case of the insects which we have just seen. However, the difference is that here there is a great distance between the corneal lens and the cylindrical lens. Most of the eye is found in the interior of the body of the animal, which is very transparent. The most important feature of this eye is that the receptor, which is tight against the cylindrical lens, is in constant movement. This is because it is in the focal plane of the anterior lens and the animal moves the second lens, with the corresponding photoreceptor, according to where it wants to direct its vision. Thus, the information arriving at the information processing system, does not arrive in parallel, as in the rest of animals, but in series, as in a television image. The sweep velocity varies between 5 lines a second and 1 line every two seconds. There is no other known case which behaves like the Copilia.

11.4. Towards a First Interpretation of the Anterior Facts

11.4.1. Initial Ideas

In the previous sections we have seen that the process of capturing a particular scene and its interpretation is not just taking a photograph of what is before us and developing it. This is what any artificial sensor does, in a mechanical way, from a simple camera to a CCD. But, if what we want to do is to profit from nature's lessons, it is necessary to add a little to that sensor, above all, if we want the system we make to be able to interpret the captured image. In other words, so that all characteristics of the image can be determined, a set of elements must be added which confers some qualities of the living organisms' sensorial system.

As is obvious, this topic is still a long way from a complete solution . Here, we will only give a brief account which I hope will serve as a starting point for future development. In the following sections we will go a little deeper into some of them.

11.4.2. Sensorial Learning

As has already be said, the reception of a sensation, or in other words, the action of the biological sensors, is nothing more than the first step in a long chain of phenomena which take place in living organisms, finally, leading to the execution of a particular action. In this chain, one of the most important processes relates the received sensation to everything stored in the memory of the living organism. A sensation is nothing unless it can be interpreted and consequently, acted upon. In the case of the visual system, this action will be, for example, the recognition of an object or of a space-time situation.

In this process there are two elements which must interact so that the living organism knows what to do: the exterior world and its brain (Fig. 11.15). From the exterior, two groups of stimuli arrive at the biological sensorial element; those coming from the object itself and those derived from the surroundings. As an example, if we try to recognise a consonant, we must extract from it only those elements constituting its essential features, whether it is written in one type of letter or another, whether it is hand-written or printed, whether the background is white or coloured, whether the environment has a lot of light or little light must be considered purely accidental. To make this possible, once the whole stimulus, the sum of all the aforementioned details has reached the brain, a type of filter must eliminate the set of accidental details. This filter reveals the essential aspects of the object, in this case the consonant, and recognises it. The way of doing this is obviously a matter of some controversy which is shown in Fig. 11.16.

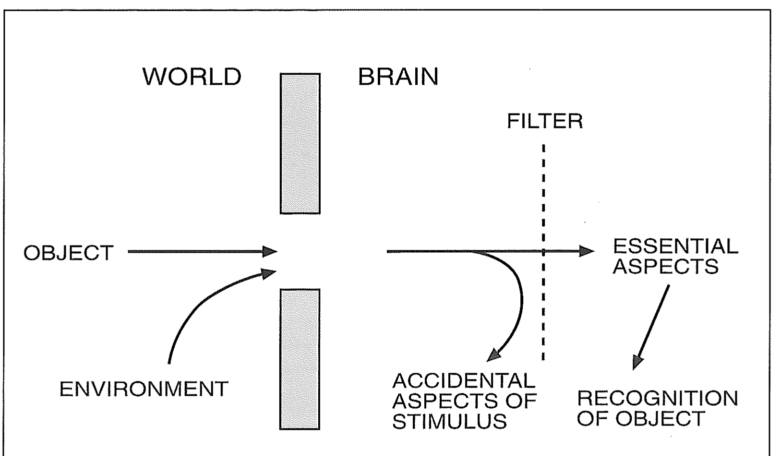

Figure 11.15. A stimulus is a coded version of the object that causes it, some aspects of it being due to the object itself and some to accidental factors. It has to be decoded by the brain filtering out the accidental properties to leave those that are essential to the object itself.

The structure is divided into two main blocks. The first refers to the sensorial part, configured as a pyramidal structure, where the general processing of the information received is carried out. It is where the general processing of the information received is carried out. The second contains everything that could be denominated visual memory, where all the previously received sensations are recorded.

The multilevel pyramid is divided into a series of layers, each layer having finer characteristics, as one goes up. This structure corresponds to the successive layers of the visual cortex, which is detailed in Fig. 11.17.

Without going into specific aspects of Fig. 11.17, and only commenting enough to have an approximate idea about the multiple tasks which can be done by the visual cortex of the mammals, we will concentrate on the general philosophy of the function of Fig. 11.16.

In the subsection dealing with the visual memory which appears in the aforementioned Figure, small rectangular areas are shown that symbolise the zones in which elemental units of information can be registered. Among them there is a series of connections which we denominate associative, while any one of them can be reached by another series of connections here denominated conductive. When these elemental units have received some information, they are activated (this is shown in the Figure by shading these memory units). The residual activation is retained for a certain amount of time depending on the type of memory.

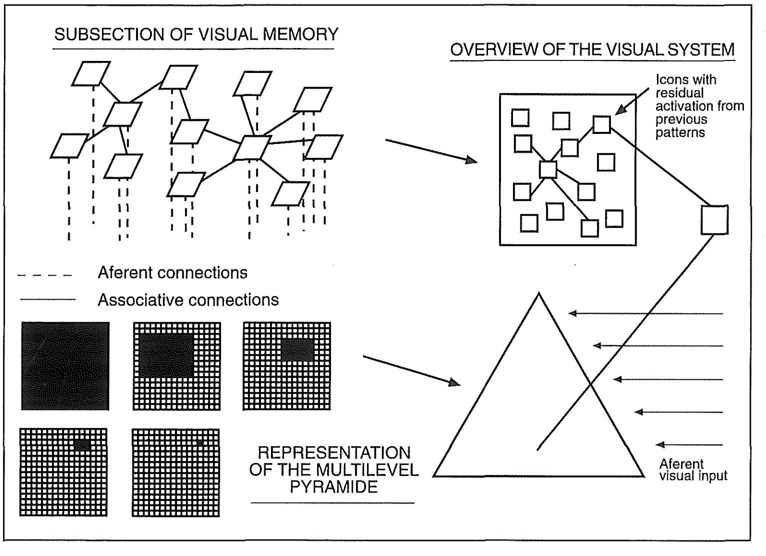

Figure 11.16. (a) Schematic description of a very small subsection of visual memory. Each icon or node has two types of possible connections, one set from within the visual memory itself (solid lines) and one set to the output of the early vision pyramid (dashed lines). (B) Schematic representation of the multi-level pyramid. Coarsest representational level is shown on the left. Finest representation shown on the bottom right. Three intermediate representations are also shown. (c) Overview of the visual system. Above is visual memory, containing tiny icons linked associatively. Below is the multi-resolution pyramid which receives afferent visual input. The linkage between these two massively parallel systems is a narrow bandwidth channel having a capacity of the order of a single icon.

Once some information has been received and partially treated by the sensorial pyramid, the relational unit puts it into contact with the visual memory subsection corresponding to the type of signal received. The response of the living organism to the received stimulus originates from the comparison between what arrives and what was already stored.

11.5 Are Concept Generating Neuronal Nets Possible?

11.5.1. General Considerations

Following from what was said previously, it seems evident that it is necessary to go deeper into the creation of structures of such a complexity that they can achieve much more sophisticated behaviour than those in use currently. Some of the examples approached up to now show that the activity of any living organism, including the most primitive, has some characteristics which are superior to the majority of those artificial systems created by man. Although in principle, it may appear not to be so, and that the tasks that these systems carry out are really complex, there is a fact to which one cannot remain indifferent. It is the relative simplicity with which a living organism carries out its functions. The simple comparison of how an animal recognises an object with the way an artificial- visual system does it, leaves no doubt. In the case of mammals, for example, in less than two dozen steps of signal processing, the visual system differentiates clearly an object shown in a photograph and the same object in real-life. If an artificial system is set this task, the complexity of data taking would, in principle, be much more complicated and, later, the processing of the data obtained would require a complex computer program, with a much greater number of instructions than that of the same stages in the living organism. Here, signals by living organisms are carried out through procedures which are basically, "hardware" procedures while in artificial systems the majority is "software". It can be noted that the complexity of the biological architectures is so great that it is impossible to emulate with modern technology. Owing to this fact, man has had to create other different methods to those used by nature to carry out certain functions. However, it is not recommendable that this path be followed indefinitely without trying to find others which can make some tasks simpler. One of these paths is that offered by the living organisms which is the fruit of millions of years of evolution. The above mentioned path has, in fact, been followed since many years ago. Since the forties numerous groups have followed approaches which suppose the imitation of what nature offers. One of the greatest achievements has been the creation of the area now known as "Neural Nets", which among other things has given rise to the creation of another technological area which has attempted to achieve "Artificial Intelligence" which is certainly artificial but does not have much intelligence. From my point of view, the path which was initiated with a nearly identical approach to that men-

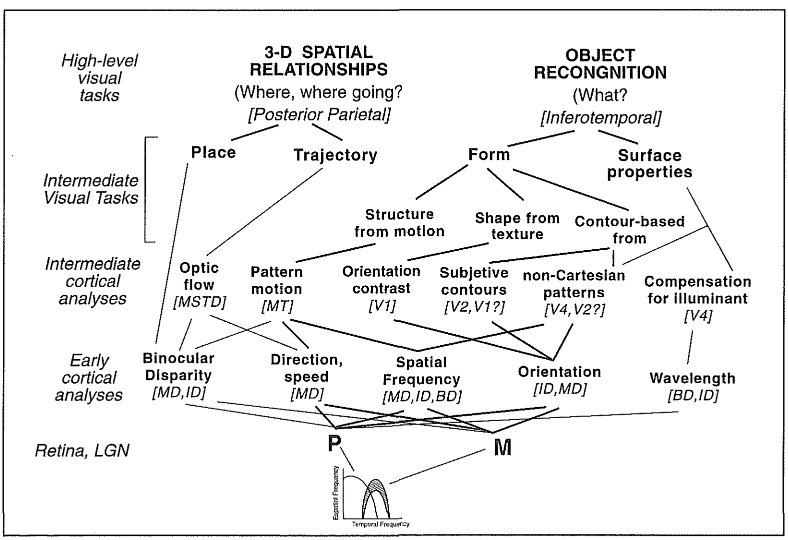

Figure 11.17. Convergence and divergence of information at different stages of visual processing. Lines represent some of the major routes of information flow from subcortical parvocellular (P) and magnocellular (M) streams (bottom level), through the selectivities made explicit in the firing patterns of cells at early and intermediate levels of cortical processes (second and third levels). At the upper levels of the diagram, the connecting lines show how these streams may contribute to several intermediate visual tasks, which in turn converge onto the two most general tasks of vision represented at the level of the inferotemporal and posterior parietal cortex.

tioned above, has gradually deviated from the initial trajectory and nowadays possesses characteristics which separate it, in many respects, form the first intention.

I believe, therefore, that we should return to what was envisaged some decades ago. With the new knowledge of Neurophisiology, and the behaviour of non-linear systems away from equilibrium, thanks to the Complexity Theory, it is possible that the new approach will be more fruitful than the previously and that new research areas will be spawned.

11.5.2. Considerations about neural and neuronal nets[4] [9].

Without trying to go deeper and losing the general character intended in these pages, we will highlight some of the characteristics which typify the behaviour of the neural and neuronal nets. To that end we will focus, almost exclusively, on the limitations of the former with respect to the latter.

The most significant limitation is the inflexibility of their behaviour. Any neural net is essentially much less flexible in its behaviour than any neuronal net integrated in the most simple biological system. Among the clearest aspects typifying this inflexibility, the following can be mentioned;

i) The behaviour of the artificial neurons, that is, those making up the neural nets, is collective but not parallel. Any change produced in the activity of any neuron affects the rest instantaneously.

On the contrary, the biological neurons behave both in a parallel and collective way. As an example there is the case of the hands, the right and the left hands can act in an independent way, which means that their behaviour is parallel, but their activity is co-ordinated by the brain, which implies that their behaviour is collective.

ii) The behaviour of the neural networks is fully determined by initial conditions. The system never forgets them and retains them, although it seems they are buried for ever.

The biological systems are much more flexible: they can forget the past, adapting their behaviour totally to the changes of the environment in which they are located.

iii) The characteristics of artificial neural systems are of the same level and scale as the behaviour they govern. Consequently, they are isolated from the microworld by a huge difference between their scales of magnitude.

The biological ones, on the contrary, relate and articulate mechanisms that cover the complete range of the possible physical-biological magnitudes, from the molecular to macroscopic level.

None of these limitations can be eliminated within the behavioural framework of classical dynamics, in which all the systems satisfy the Lipschitz[5] condition that guarantees the uniqueness of the solutions of the problem under study, once the initial conditions are determined. In other words, the temporal evolution of the system is predictable and its behaviour in the future is perfectly determined.

On the one hand, the neural nets are only capable of processing information they receive. They can learn, thanks to examples supplied to them, store data in their memory and recognise patterns. However, all these activities are completely predictable, as has been said already, since they were predeter-

[4] The difference I want to highlight between neuronal nets and neural nets is that the first are those formed by a set of biological neurons making up a suitable structure to carry out a particular function in a living organism. Neural nets, on the contrary, are those architectures created by man which, although in some of their principles can function like biological ones, have a different global philosophy from the neuronal ones.

[5] The Lipschitz condition, which guarantees the uniqueness of the solutions to some fixed initial conditions, is fulfilled when all the derivatives of type $\partial u_i{}'/\partial u_j$ with $u_i(t)$ as the soma potential of the ith neuron exist and are limited.

mined owing to the original dynamic structure.

On the other hand, the neuronal nets are apparently capable of extracting information from nothing. The ideas are generated in the brain and, in many cases, have no relation to those that were originally supplied. In fact, this behaviour originates from the background which is always present in any biological system. This background implies minute perturbations which interact with the unpredictability of all non-classical systems and consequently allow it to evolve along an unpredictable trajectory.

There is, however, quite noteworthy evidence that the brain, along with the complete sensorial system, behaves as a disipative non-linear system. The data which can be extracted from an electroencephalogram shows this very clearly. At the same time, while the finite machines operate with simple bits of information, the brain, paradigm of non-linear dynamics, operates with complex blocks of information which are like patterns containing the information of interest to the subject.

The consideration of a theory, capable of comprising all the anterior concepts, without the restrictions imposed by linear dynamics, and which can be applied to the processes that take place in the brain to be able, later, to simulate it in a true way, constitutes one of the most attractive challenges for the coming years. Here, the problem has only been brought to light.

11.5.3. Synchronisation of Chaotic Systems.

Another possible approach to solve the system considered is to adopt guidelines used in other Scientific and Technology fields. We are referring to the introduction in the area of sensorial physiology of concepts of complexity theory.

As has already been commented, the determination by living organisms of a certain external stimulus does not only presuppose that this stimulus has incided on the corresponding sensorial element. Furthermore, it is necessary that the whole set of organs related to this sensation, and which make up the living organism, are coordinated giving rise to a joint action. So, the capture by the eye, of a certain image implies not only recognising it but at the same time, extracting from this image the most significant information for the desired purpose, interpreting it, determining what type of action to take and, finally, executing it. All this implies the establishment of a set of mechanisms which must articulate harmonically and be guided by a unique purpose.

In the same way, as has been indicated in a previous section, that most of the brain function has been determined thanks to malfunctions derived from one of its pathologies, the proposal we make in this case is to consider a possible coordination mechanism among parts of a system in such a way that, if one of them displays irregular behaviour, this behaviour is transferred to other equivalent ones which are located in its surroundings. If a region of the sensorial system stops behaving in the foreseen way, the system as a whole would then show equivalent behaviour. An example of this situation occurs in the case of hallucinations suffered by a patient who sees certain forms or hears voices which, in reality, do not exist. The basis of this mechanism can be synchronisation of chaotic systems, analogous to what is considered in communications systems.

In general terms, communications depend on signals, variable with time in an intentional way or not, that are transmitted by one system and received by another. This dependency with time implies that, in some part of the complete communication system, there are one or more physical quantities which change their state. This change can be intentional or not and constitutes part of the system or not, but the tangible fact is that the signals intervening in the transmission channel are directly related to the dynamics of that system. This dynamic has been determined up to now, by laws derived from behaviour which was assumed to be causal while the latest approaches indicate that there are many other parameters in play which determine much more complex behaviour than that supposed initially. Owing to this fact, the only method of dealing with these phenomena is by using non-linear dynamics, a long way from the methods used up to now, which permits, or at least tries to, explain how any system evolves with time. This evolution, highly studied in conventional systems, we presuppose can be extended to other systems, like biological ones, in which an exchange of information is always present.

This is neither the time nor the place to initiate a profound treatment of this topic. As has been said, the object is only to think about a possible path and to leave it open so that, at some other time, it can be analysed in more detail. We will only see here the part referring to its possible use in getting to know particular pathologies of the sensorial system. Without specifying which, and estimating that the model can be valid for functional abnormalities with different causes, it is considered implicit that one of them exists in the sensorial system. In it, as in many others, a malfunction of a small part leads to an erroneous interpretation in the system, considered as a whole. The problem considered is what repercussions this malfunction has on the surroundings and how other parts of the same sensorial system can manage to behave in an analogous way to the abnormal one.

Our supposition is that this coordination of behaviour is analogous to the synchronisation of chaotic systems in communications. Among the various possible methods of synchronisation, the one to be presented here is given by Pecora and Carroll [10].

The basic scheme appears in Fig. 11.18. As can be seen, it is constituted by two large blocks which make up two systems that could work in an isolated way generating a particular behaviour. In a general case, both can be the emitter and the receiver of a communications system. In the specific case we are dealing with here, both blocks can in principle be generators of chaotic signals. For this, both should be equal, that is, made up of three subsystems, in an analogous way to the one on the left of the figure. This chaotic behaviour, maybe the clearest and paradigmatic example of the non-linear response of a system, would only appear on the fulfilment of a series of conditions between the system's parameters and the initial

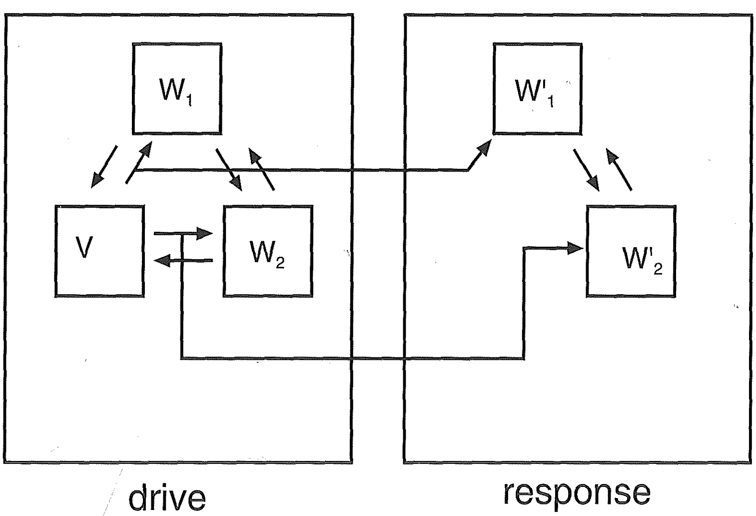

Figure 11.18. Schematic for creating a synchronizing chaotic system.

conditions imposed. Even if this were verified in the two systems appearing in Fig. 11.18, the resultant chaos would not be the same in both. That is, if a temporal representation were made of the signal obtained from both, it could be seen that the instantaneous values would not be the same. The chaos, if analysed by any of the usual methods, would have the same characteristics in both systems, but the values at each particular instant of time would be different.

The method of getting both systems to work with identical behaviour, both in time and mode, is as derived in Fig. 11.18. As can be seen, the first system, A, is divided into three subsystems. In each subsystem there is one of the critical parameters for the obtention of chaos, which is derived from the Poicaré - Bendixon Theory. In the second system, B, there are only two subsystems. This means that if A can give rise to chaotic behaviour, the second, since one of the parts is missing would not be capable of doing so. But if one of the signals generated in A is supplied to B in the way shown in Fig. 11.18 the behaviour of both would be identical. Not only are both capable of generating chaos, but furthermore, the chaos is the same at any instant.

If the equation determining the system behaviour is

$$dx / dt = F(x) \tag{11.3}$$

on dividing the system into the blocks, shown in Fig. 11.18, the vector x which characterises its behaviour is also divided into two subvectors x=(v,w), in such a way that if x is a-dimensional, w will be m-dimensional and v, (n-m)-dimensional. The equations of movement are now

$$dv / dt = g(v,w)$$
$$dw / dt = h(v,w)$$

where f=(g,h). The equation corresponding to B will be

$$dw / dt = h(v,w)$$

the condition which must be fulfilled so that the w' values converge towards the w ones is, as is logical, that the difference w-w'=..w tending to 0. And that this convergence can be determined as a function of the behaviour of the equation governing the dynamics of the whole system, that is

$$d(\Delta w) / dt = Dh(v,w).\ \Delta w$$

where D is the Jacobian of the function.

This equation determines the behaviour of the system and also whether it is possible or not to synchronise the two blocks, for example, if D is a constant, its solution would simply be

$$\Delta w(t) = \exp(Dh.\ t)\,\Delta w(0) \tag{11.4}$$

so, depending on the values of Dh, the solution converges to zero (that is, the system permits synchronisation) or not (implying an asynchronous situation).

The application of the above to our case, although without solving, can be *feasible* and, in fact, approachable in the short term for simple cases. The most specific seems to be the study carried out some time ago to characterise the chaos obtained from the axon of the giant squid, using the Hodgkin and Huxley equations. The extension to perturbations in the visual system does not appear to be too complex. The first stage would be to obtain the equation corresponding to the dynamics of the system under consideration. However, we will not go into this topic here.

11.6 Conclusions

Throughout the previous text we have tried to offer a personal vision of what have been denominated photobiological sensors. Our objective was, as on other occasions, to try to extract some lessons from them which allow us to elaborate their replicas. Among the characteristics which we have highlighted, in them, and which should serve as a model for new design approaches, of biophotonic sensors and may be even of other sensors, the following might be mentioned, in a concise and unified way compared to the disperse way they were commented before:

— The information received from the exterior is processed in a selective way.

— The images are interpreted in relation to their context, both spatial and temporal.

— The memory of previous situations affects the way of understanding the images.

— The sensorial organs of each species are adapted to the most immediate survival and reproduction necessities.

— The processing of the received information is carried out in different zones and levels of the visual system, depending on the degree of abstraction required.

As a consequence of the above, and as recommendations to be taken into account when designing an artificial sensorial system, the following could be considered:

— The sensorial element has to be perfectly adapted to the functions it has to fulfil. It must exclude any influence by factors not related to the object parameter of recognition.

— The analysis system must be adapted to the desired type of recognition. The processed signals can be analogous to those produced in other concurrent sensorial systems. In this case it is the system architecture which must determine the origin of the signal.

— The number of processing stages must be a function of the number of magnitudes to be sensed and their level of abstraction.

— The economy (of resources, concepts, adaptation to the enviroment) must prevail over any other consideration.

— The memory and the surroundings strongly influence the results obtained.

This chapter has centred almost exclusively on some aspects of the visual sensorial systems which we had not reported previously [11]. Owing to this, we have not even mentioned a fundamental part of the visual system of the mammals: The neuronal architecture that processes the signals received in the retina and which achieves the recognition and differentiation of distinct signals. As doing it again here would be superfluous, we preferred to leave it out. For the same reasons neither have we said anything about the way in which the individual neurons propagate the signals through their axons.

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